

# Transversity from two pion interference fragmentation

Jun She and Yang Huang

*School of Physics, Peking University, Beijing 100871, China*

Vincenzo Barone

*Di.S.T.A., Università del Piemonte Orientale “A. Avogadro”,*

*and INFN, Gruppo Collegato di Alessandria, 15100 Alessandria, Italy*

Bo-Qiang Ma\*

*School of Physics and State Key Laboratory of Nuclear Physics and Technology,*

*Peking University, Beijing 100871, China*

## Abstract

We present calculation on the azimuthal spin asymmetries for pion pair production in semi-inclusive deep inelastic scattering (SIDIS) process at both HERMES and COMPASS kinematics, with transversely polarized proton, deuteron and neutron targets. We calculate the asymmetry by adopting a set of parametrization of the interference fragmentation functions and two different models for the transversity. We find that the result for the proton target is insensitive to the approaches of the transversity but more helpful to understand the interference fragmentation functions. However, for the neutron target, which can be obtained through using deuteron and  $^3\text{He}$  targets, we find different predictions for different approaches to the transversity. Thus probing the two pion interference fragmentation from the neutron can provide us more interesting information on the transversity.

PACS numbers: 13.60.Le, 13.85.Ni, 13.87.Fh, 13.88.+e

---

\*Electronic address: mabq@phy.pku.edu.cn

## I. INTRODUCTION

At leading twist, the internal structure of the nucleon can be described by three fundamental distribution functions. They are the unpolarized, the longitudinal and the transversity distribution functions. The former two have been well known, but the last one – transversity [1], is less known both theoretically and experimentally. The difficulty lies in its chiral-odd property, which makes it inaccessible in inclusive deep inelastic scattering (DIS) process. However, transversity can manifest itself through Collins mechanism [2] in single hadron production where the chiral-odd distribution function (DF) couples with an also chiral-odd fragmentation function (FF), the so called Collins function. By observing the single spin asymmetry (SSA) phenomena, we can extract the information on the transversity and the Collins function. HERMES collaboration [3] and COMPASS collaboration [4] have already published their data, reporting their observation of the non-zero SSA. Some work [5] has been done to extract the transversity and Collins function from the data. In future, JLab (Jefferson Laboratory) has also planned to measure the transversity through the same process but with the  $^3\text{He}$  target [6]. We expect further exploration to give more information.

However, difficulty still exists for reliable measurements of transversity. Since the transversity and the Collins function always appear together in the single hadron production case, they in fact cannot be directly measured independently. An alternative way to measure transversity is to detect two unpolarized leading hadrons in the final state, which was suggested first by Collins, Ladinsky, Heppelmann [7] and then by Jaffe, Jin and Tang [8]. In two hadron leptonproduction process, the transversity gets factorized at leading twist through a new chiral-odd FF, usually called the interference FF. The new introduced FF is still unknown yet, but it can be cleanly measured in  $e^+e^-$  annihilation at Belle. Until now, HERMES [9] and COMPASS [10] have already published their preliminary data on two hadron production process with unpolarized beam and transversely polarized proton or deuteron target, which made a first step in understanding the new FF. On the theoretical side, some models have been put forward to calculate the interference FF for  $\pi^+\pi^-$  pair production [8, 11, 12]. In Ref. [12], Bacchetta and Radici also gave their prediction at HERMES and COMPASS kinematics, using different parametrizations of transversity. In this paper, we will also give predictions on SSA both at HERMES and COMPASS kinematics

and with various targets. For the interference FFs, we will adopt the parametrization provided by Ref. [12], while for the transversity, we will use two different models, the SU(6) quark-diquark model and the pQCD based counting rule analysis.

## II. CROSS SECTIONS AND THE ASYMMETRY

The asymmetry measured by the experiment is defined as:

$$\begin{aligned} A_{UT}(\phi_R, \phi_S, \theta) &= \frac{1}{|S_T|} \frac{N^\uparrow(\phi_R, \phi_S, \theta)/N_{\text{DIS}}^\uparrow - N^\downarrow(\phi_R, \phi_S, \theta)/N_{\text{DIS}}^\downarrow}{N^\uparrow(\phi_R, \phi_S, \theta)/N_{\text{DIS}}^\uparrow + N^\downarrow(\phi_R, \phi_S, \theta)/N_{\text{DIS}}^\downarrow} \\ &= \frac{\sigma_{UT}}{\sigma_{UU}}, \end{aligned} \quad (1)$$

where  $UT$  refers to unpolarized beam and transversely polarized target. The asymmetry is evaluated as a function of the angles  $\phi_R$ ,  $\phi_S$  and  $\theta$ .  $\phi_R$  denotes the azimuthal angle of the detected two hadron plane with respect to the lepton plane, and  $\phi_S$  denotes the azimuthal angle of the polarization vector  $\vec{S}_T$  with respect to the lepton plane.  $\theta$  is the polar angle of the first hadron in the hadron pair's center-of-mass frame with respect to the direction of the summed hadron momentum in the lab frame<sup>1</sup>.

Consider the process  $e \vec{N} \longrightarrow e' h_1 h_2 X$ , where the hadrons  $h_1$  and  $h_2$  are produced hadrons in the current fragmentation region. An electron with momentum  $l$  scatters off a proton target with mass  $M$  and momentum  $P$ , via the exchange of a virtual photon with momentum transfer  $q = l - l'$ . Inside the proton, a quark with initial momentum  $p$  changes to a state with momentum  $k = p + q$  after the photon hit it. We define the light-cone variable  $x = p^+/P^+$ , which represents the fraction of target momentum carried by the quark. The detected two hadrons have momenta  $P_1$  and  $P_2$ , masses  $M_1$  and  $M_2$ , and total invariant mass  $M_h^2 = (P_1 + P_2)^2$ . We introduce the vectors  $P_h = P_1 + P_2$  and  $R = (P_1 - P_2)/2$ , i.e., the total and relative momenta of the hadron pair, respectively. We have

$$|\vec{R}| = \frac{1}{2} \sqrt{M_h^2 - 2(M_1^2 + M_2^2)} = \frac{1}{2} \sqrt{M_h^2 - 4m_\pi^2}, \quad (2)$$

if only  $\pi^+\pi^-$  pairs are considered now. Similar to  $x$ , we define  $z = P_h^-/k^-$ , which represents the fraction of fragmenting quark momentum carried by the produced hadrons. We will also

---

<sup>1</sup> The angle definitions here are consistent with the ‘‘Trento Conventions’’ [13].

introduce a light-cone fraction  $\zeta = 2R^-/P_h^-$ , which describes how the total momentum of the pair is split into the two hadrons,

$$\zeta = \frac{2R^-}{P_h^-} = -\frac{2|\vec{R}|}{M_h} \cos \theta. \quad (3)$$

With the definitions above, the cross section up to leading twist can be expressed as: [14]<sup>2</sup>

$$\frac{d^7\sigma_{UU}}{d\zeta dM_h^2 d\phi_R dz dx dy d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y} \sum_a e_a^2 A(y) f^a(x) D_1^a(z, \zeta, M_h^2), \quad (4)$$

$$\begin{aligned} \frac{d^7\sigma_{UT}}{d\zeta dM_h^2 d\phi_R dz dx dy d\phi_S} &= -\frac{\alpha^2}{2\pi Q^2 y} |\vec{S}_T| \sum_a e_a^2 B(y) \sin(\phi_R + \phi_S) \sin \theta \\ &\times \frac{|R|}{M_h} \delta f^a(x) H_1^{\lessgtr a}(z, \zeta, M_h^2), \end{aligned} \quad (5)$$

with  $A(y) = 1 - y + y^2/2$  and  $B(y) = 1 - y$ . Here,  $f(x)$  and  $\delta f(x)$  denote the unpolarized and the transversity distribution functions respectively.  $D_1(z, \zeta, M_h^2)$  and  $H_1^{\lessgtr a}(z, \zeta, M_h^2)$  are the new introduced interference FFs, describing a quark fragmenting to a pair of hadrons, for example,  $\pi^+\pi^-$  pairs. After integration of  $\phi_R$ ,  $\phi_S$  and  $\zeta$ , we define the weighted asymmetry:

$$\begin{aligned} A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(y, x, z, M_h^2) &= \frac{2}{|\vec{S}_T|} \frac{\int d\phi_S d\phi_R d\zeta \sin(\phi_R + \phi_S) / \sin \theta d^7\sigma_{UT}}{\int d\phi_S d\phi_R d\zeta d^7\sigma_{UU}} \\ &= -\frac{\frac{B(y)}{xy^2} \sum_a e_a^2 \delta f^a(x) \int d\zeta \frac{|\vec{R}|}{M_h} H_1^{\lessgtr a}(z, \zeta, M_h^2)}{\frac{A(y)}{xy^2} \sum_a e_a^2 f^a(x) \int d\zeta D_1^a(z, \zeta, M_h^2)}. \end{aligned} \quad (6)$$

More details on the interference FFs will be given in the next section.

### III. PARAMETRIZATION OF DISTRIBUTION AND FRAGMENTATION FUNCTIONS

#### A. Distribution Functions

In this paper we will adopt two models: the SU(6) quark-diquark model [15, 16, 17] and the pQCD based counting rule analysis [18, 19, 20, 21, 22] to get the transversity distributions. Both two models have given pretty good descriptions on the longitudinal polarized parton distribution functions [23]. A recent work [24] showed that the prediction based on the two models for transversity was also compatible with the current experiment

---

<sup>2</sup> Also see this article for sub-leading twist expression.

data. We can say that both models reflect the main feature of the nucleon structure in the mediate  $x$  region. But two models behave differently when  $x \rightarrow 1$ : the SU(6) quark-spectator-diquark model [17] predicts  $\delta d(x)/d(x) \rightarrow -1/3$ , while the pQCD based counting rule analysis [20] predicts  $\delta d(x)/d(x) \rightarrow 1$ . In a recent literature [5], Anselmino *et al.* extracted the transversity distribution for  $u$  and  $d$  quarks from the now available data, and showed some evidence that  $\delta u(x)$  and  $\delta d(x)$  to be opposite in sign, with  $|\delta d(x)|$  smaller than  $|\delta u(x)|$ . This seems to be coincidence with the SU(6) quark-diquark model qualitatively, but it clearly shows that  $\delta d(x)/d(x) \rightarrow 0$  when  $x \rightarrow 1$ , which is coincidence with neither model we used in this paper at large  $x$  region. The correctness of different parametrization is still unclear, and need to be checked by more experiments.

For the SU(6) quark-diquark model, we will adopt one set of the unpolarized quark distribution parametrization as a input, and then use theoretical relations to connect the quark transversity distributions with the unpolarized distributions [17, 26]:

$$\begin{aligned}\delta u_v(x) &= [u_v(x) - \frac{1}{2}d_v(x)]\hat{W}_S(x) - \frac{1}{6}d_v(x)\hat{W}_V(x), \\ \delta d_v(x) &= -\frac{1}{3}d_v(x)\hat{W}_V(x),\end{aligned}\tag{7}$$

$\hat{W}_S(x)$  and  $\hat{W}_V(x)$  are the Melosh-Wigner rotation factors [26, 27, 28] for spectator scalar and vector diquarks, which come from the relativistic effect of quark transversal motions [29]. This model predicts  $d_v(x)/u_v(x) \rightarrow 0$  when  $x \rightarrow 1$ , which is compatible with the available experiment data.

For the pQCD based analysis, we adopt the parametrization

$$\begin{aligned}u_v^{pQCD}(x) &= u_v^{para}(x), & d_v^{pQCD}(x) &= \frac{d_v^{th}(x)}{u_v^{th}(x)}u_v^{para}(x), \\ \delta u_v^{pQCD}(x) &= \frac{\delta u_v^{th}(x)}{u_v^{th}(x)}u_v^{para}(x), & \delta d_v^{pQCD}(x) &= \frac{\delta d_v^{th}(x)}{u_v^{th}(x)}u_v^{para}(x),\end{aligned}\tag{8}$$

where the superscripts “th” means the theoretical calculation in the pQCD analysis [30, 31], and “para” means the input from parametrization. The pure theoretical calculation in this model predicts that  $d_v(x)/u_v(x) \rightarrow 1/5$  when  $x \rightarrow 1$ . So we use a factor  $u_v^{para}(x)/u_v^{th}$  to adjust each pure theoretically calculated quantity to a more realistic pQCD model quantity.

In this paper, we will use the CTEQ6L [32] parametrization<sup>3</sup> as the input for both models

---

<sup>3</sup> This parametrization gives that  $d_v(x)/u_v(x) \rightarrow 0$  when  $x \rightarrow 1$ , which is coincidence with the current data.

to get the unpolarized parton distribution functions. Detailed constructions of the quark distributions can be found in Ref. [30, 31, 33].

## B. Interference Fragmentation Functions

The so called interference FFs  $D_1(z, \zeta, M_h^2)$  and  $H_1^\zeta(z, \zeta, M_h^2)$  describe a quark splitting into a pair of unpolarized hadrons inside the same jet. Different models [8, 11, 12] have given their calculated results on the interference FFs. In this paper, we will follow the parametrization given by Ref. [12], where they used the spectator model to get the result.

From Eq. 3, we find that the dependence on  $\zeta$  can be expressed on  $\cos\theta$ . Expanding the hadron pair system in relative partial waves, we get: [34]

$$D_1^a(z, \cos\theta, M_h^2) \approx D_{1,oo}^a(z, M_h^2) + D_{1,ol}^a(z, M_h^2) \cos\theta + D_{1,ul}^a(z, M_h^2) \frac{3\cos^2\theta - 1}{4}, \quad (9)$$

$$H_1^{\zeta a}(z, \cos\theta, M_h^2) \approx H_{1,ot}^{\zeta a}(z, M_h^2) + H_{1,lt}^{\zeta a}(z, M_h^2) \cos\theta. \quad (10)$$

Integrating over  $\zeta$ , i.e., the  $\cos\theta$ , we can easily find that only  $D_{1,oo}^a$  and  $H_{1,ot}^{\zeta a}$  contribute to the final result. The factor  $|\vec{R}|/M_h$  appearing due to the Jacobian can be absorbed in the definition of integrated interference FFs. The explicit expressions for  $D_{1,oo}^a$  and  $H_{1,ot}^{\zeta a}$  can be found in Ref. [12].

## IV. NUMERICAL CALCULATIONS

We present the final formula for calculating the asymmetry:

$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(y, x, z, M_h^2) = -\frac{\frac{1-y}{xy^2}}{\frac{1-y+y^2/2}{xy^2}} \frac{|\vec{R}|}{M_h} \frac{\sum_a e_a^2 \delta f^a(x) H_{1,ot}^{\zeta a}(z, M_h^2)}{\sum_a e_a^2 f^a(x) D_{1,oo}^a(z, M_h^2)}. \quad (11)$$

By integrating through various ways on the numerator and denominator, we can get the asymmetry depending on different kinematical variables. In this paper, the dependencies on  $M_h$ ,  $x$  and  $z$  are calculated.

For each target, we will perform the numerical calculations under both HERMES and COMPASS experiment cuts. In the HERMES experiment, the kinematical cuts are:

$$Q^2 > 1 \text{ GeV}^2, \quad W > 2 \text{ GeV}, \quad 0.1 < y < 0.85, \quad 0.2 < z < 0.7, \quad 0.5 < M_h < 1 \text{ GeV}. \quad (12)$$

For the  $Q^2$  and  $W$  used in the integration over  $y$  and  $x$ , we use the relations

$$Q^2 = sxy, \quad W^2 = sy(1-x) + M^2, \quad (13)$$

with  $s = 2ME = 51.8\text{GeV}^2$  in the HERMES experiments.

For COMPASS, the kinematics are:

$$\begin{aligned} s &= 300 \text{ GeV}^2, \quad Q > 1.0 \text{ GeV}, \quad W > 5.0 \text{ GeV}, \\ 0.1 < y < 0.9, \quad 0.1 < z < 0.9, \quad 0.3 < M_h < 2.5 \text{ GeV}. \end{aligned} \tag{14}$$

We notice first that the beam energy is extremely high ( $\mu^+$  beam with 160GeV) that the COMPASS experiment can detect very small  $x$  region, so for convenience, we will adopt the logarithm coordinate. Second, COMPASS can reach a higher  $M_h$  than HERMES, but the model for the interference FFs does not consider the contributions from resonances with higher masses. We argue that the parametrization should be modified for higher invariant mass of the pair system, so here we only present the calculation up to the HERMES cut for  $M_h$ .

### A. Proton target

The numerical result for proton target are shown in Fig. 1 and Fig. 2.

From Fig. 1 and Fig. 2, we can see that different models for the transversity give almost the same predictions on the asymmetry for the proton target. This is because the proton target is dominated by  $u$  quarks, and the two models give similar predictions on  $u$  quark distributions [35]. Besides this, the contribution from  $u$  quarks should be magnified by 4 times due to the charge. So we conclude that the result is insensitive to the models of transversity for proton target, thus from this experiment, we cannot distinguish the two models. However, in the mediate  $x$  region, this gives us a chance to measure the unknown interference FFs, which is helpful to explore the new domain. Now, different models give different predictions on the interference FFs. According to Ref. [8], the FF was anticipated to change sign around  $\rho$  mass, while in Ref. [11, 12], they predicted a peak at  $\rho$  mass. Even between the results in Ref. [11] and Ref. [12], there are also slightly differences. If the conclusion that the asymmetry is insensitive to different approaches of the transversity holds, we expect the experiments to publish more data on proton target to clarify the details on the interference FFs.

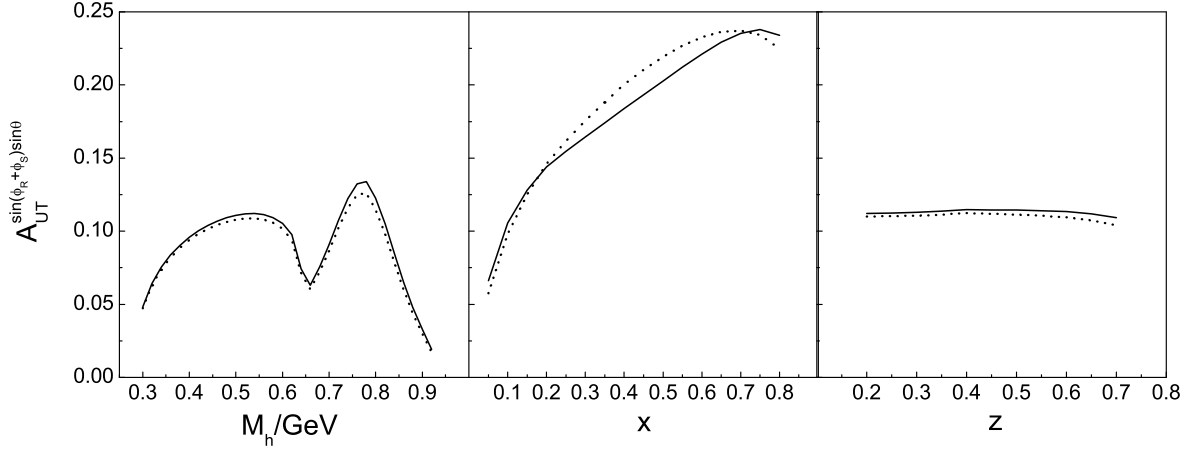


FIG. 1:  $A_{UT}^{\sin(\phi_R + \phi_S) \sin \theta}$  at HERMES kinematics for a transversely polarized proton target as a function of  $M_h$ ,  $x$  and  $z$  respectively. The solid lines and dotted lines correspond to the results evaluated from SU(6) quark-diquark model and pQCD based counting rules, respectively.

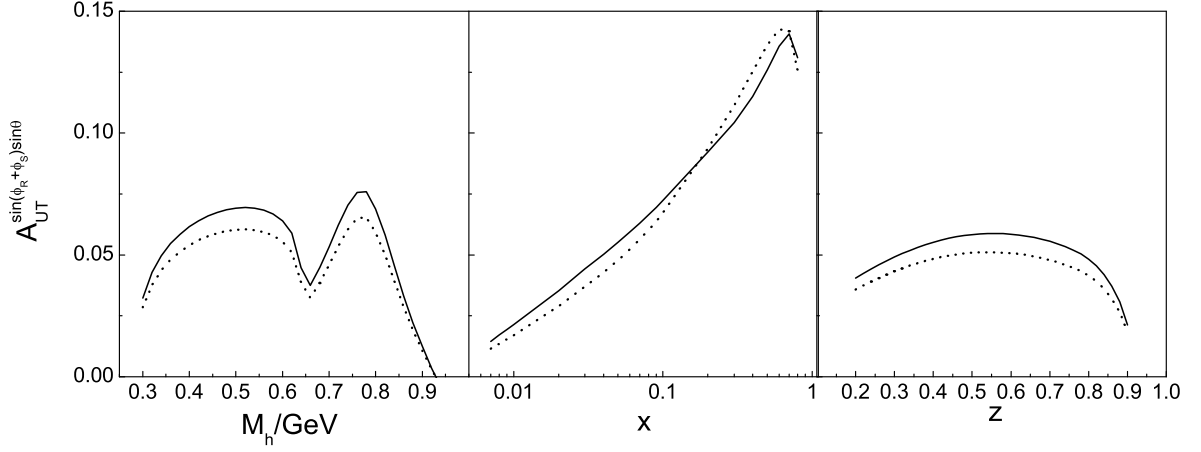


FIG. 2: The same as Fig. 1, but at COMPASS kinematics

## B. Deuteron target

The result for deuteron target is shown in Fig. 3 and Fig. 4. Inside the deuteron, the  $u$  and  $d$  quarks have the same distribution, and because of the charge,  $u$  quarks still dominant



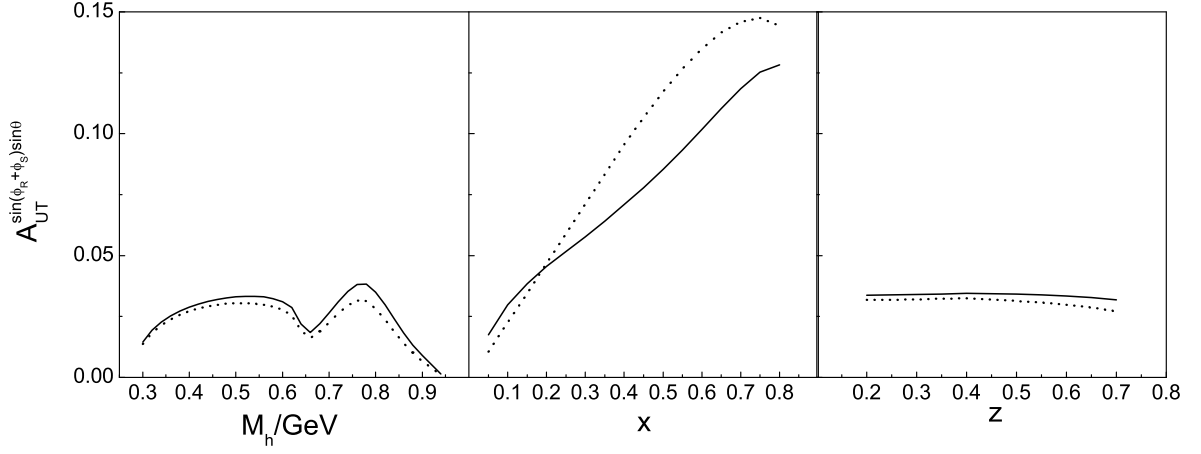


FIG. 3: The same as Fig. 1, but for deuteron target.

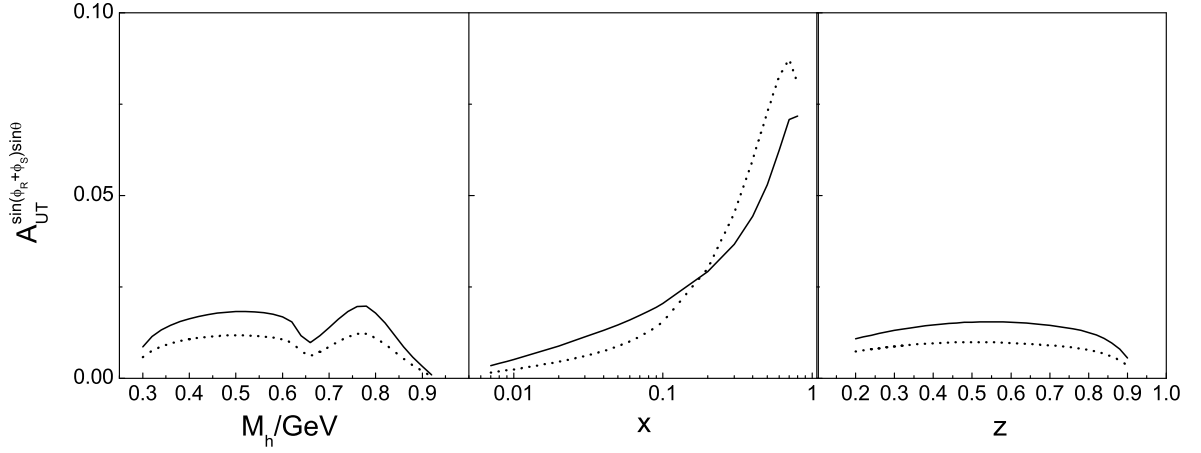


FIG. 4: Similar to Fig. 2, but for deuteron target.

here, and the asymmetry is still not so sensitive to different models of the transversity. So the deuteron target can also be used to measure the interference FFs. Combining the experiment data from the proton and deuteron targets, we can get abundant information not only on the interference FFs but also the transversity distributions, especially for  $u$  quarks.

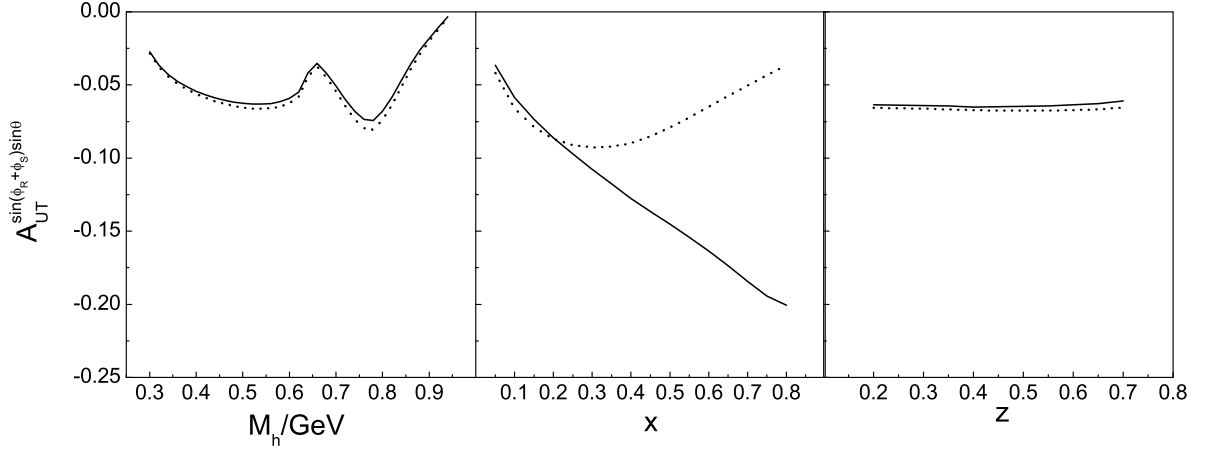


FIG. 5: The same as Fig. 1, but the neutron target is assumed here.

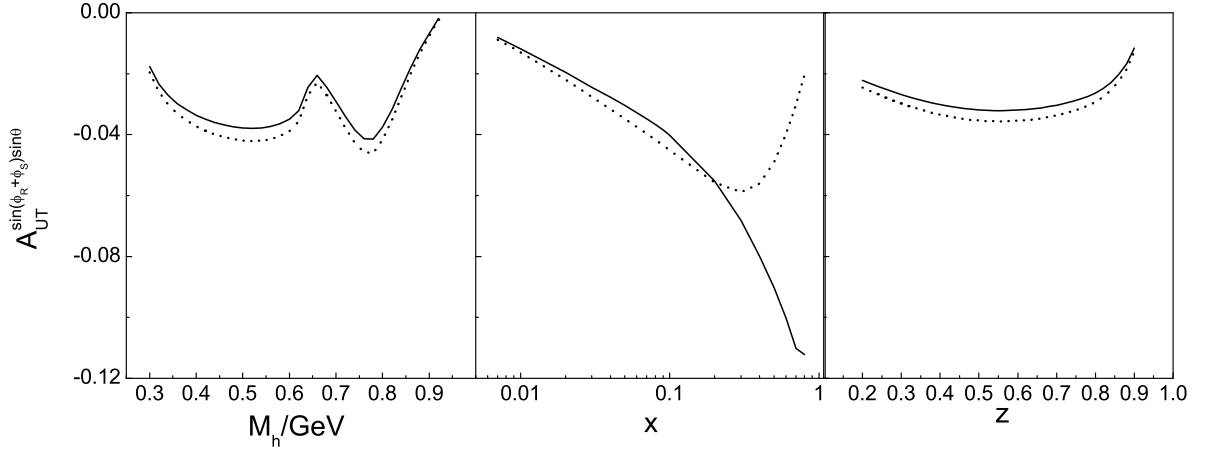


FIG. 6: The same as Fig. 2, but the neutron target is assumed here.

### C. Neutron target

Although from the data on deuteron target, we can get a first glance at the transversity distribution for  $d$  quarks, we suggest a directly measurement using the neutron target. Fig. 5 and Fig. 6 show the result on the neutron target. Due to the fact that the information on  $z$ -dependence and  $M_h$ -dependence is only contained in the interference FFs, two models

should give nearly the same prediction on the  $z$  and  $M_h$  dependence of the asymmetry, which is similar to the proton and deuteron targets. But for  $x$ -dependence, because  $d$  quarks dominate in the neutron target, and two models give quite different predictions on the  $d$  quark distributions [35], the two models might exhibit their differences here, even if the contribution from  $d$  quarks is suppressed by a factor of 4 originated from the square of the electric charge compared with  $u$  quarks. As the figures show, different models for the transversity predict differently on the asymmetry when  $x$  increases, thus this is helpful for us to distinguish the two models. However, we should notice that this effect is apparent only in the large  $x$  region. Both HERMES and COMPASS did the experiment in the relative low  $x$  region, and this difference is not so obvious there. So we expect further experiments will reach higher  $x$  region to help us distinguish the models. Another problem is that it is difficult to acquire free neutron target, so  $^3\text{He}$  target is suggested, which can be considered as an effectively free neutron, because two protons inside the nucleus form a spin singlet. JLab has planned measurements on the  $^3\text{He}$  target, so we look forward to the result from JLab.

Careful analysis with data from both proton and deuteron targets may also provide an extraction of neutron result. This can be done by combining both HERMES and COMPASS experiments, or COMPASS perform precision measurements on both proton and deuteron targets respectively.

Unlike the case in single pion production where the the predictions on the neutron are insensitive to different models [24], the double pion production are ideal to distinguish between different model predictions. The first reason is that there is no dilation caused by unfavored fragmentation functions as in the single pion case, so that the contribution from the  $d$ -distribution of the nucleon (in fact it is  $u$ -distribution in the neutron) can manifest itself more clearly in double pion interference fragmentation. Another important reason is that the two pion interference fragmentation function causes the  $d$ -quark contribution to have an opposite sign compared to that of the  $u$ -quark contribution in the single spin asymmetry formula [12], so that the calculated single spin asymmetries are always negative in both the two models for the neutron case. More explicitly, we can predict the large

$x$ -behavior

$$A_n = -\frac{1}{9} \times \frac{21}{19} A_p, \quad \text{for pQCD inspired model;} \quad (15)$$

$$A_n = -A_p, \quad \text{for quark-diquark model,} \quad (16)$$

at  $x \rightarrow 1$  for the single spin asymmetry. This provides a strong motivation to do experiments on extracting the neutron result of single spin asymmetry in double hadron production.

## V. SUMMARY

Transversity distribution is the less known piece in understanding the spin structure of the nucleon due to its chiral-odd nature. Single spin asymmetry of single hadron production in semi-inclusive deep inelastic scattering (SIDIS) provide a way accessing the transversity, in which the transversity distribution couples with an also chiral-odd fragmentation function (FF), the collins function. Another interesting way to measure the transversity is through observing single spin asymmetry (SSA) in double hadron production, where transversity gets factorized with the so called interference FF. One advantage for this method is that the interference FF can be measured separately in the  $e^+e^-$  annihilation process, so that we can get a clean result on transversity. HERMES has already finished the experiment and will publish their data in near future. COMPASS has also published their preliminary data and is still accumulating data. In this paper, we present numerical calculation for the proton, deuteron and neutron target respectively at the HERMES and COMPASS kinematic region, using two models for transversity and a set of parametrization of interference FFs provided by Ref. [12]. We found that two models, the SU(6) quark-diquark model and the pQCD based counting rule analysis give quite similar prediction at HERMES and COMPASS kinematics for the proton and deuteron target, i.e., the result is insensitive to different approaches of the transversity. Thus we argue that the HERMES and COMPASS experiment can provide rich information on the interference FFs. For the neutron target, we found that the two models give different predictions at large  $x$  region, which is helpful to distinguish them. So we suggest doing experiments with  $^3\text{He}$  target (an effective neutron target) at large  $x$  region to give more information, especially that on the transversity of  $d$  quarks. Maybe JLab will bring us exciting results. Careful analysis of data from both proton and deuteron targets by HERMES and COMPASS might be also useful to extract the neutron result, for the sake to

confront different theoretical predictions on transversity.

## **VI. ACKNOWLEDGEMENT**

We are grateful to Xiaorui Lu and Gunar Schnell for useful discussion. This work is partially supported by National Natural Science Foundation of China (Nos. 10421503, 10575003, 10528510), by the Key Grant Project of Chinese Ministry of Education (No. 305001), by the Research Fund for the Doctoral Program of Higher Education (China), and by the Italian Ministry of University and Research (PRIN 2007).

- 
- [1] For a review on transversity distribution, see, e.g., V. Barone, A. Drago, and P.G. Ratcliffe, Phys. Rep. **359**, 1 (2002).
  - [2] J. C. Collins, Nucl. Phys. **B 396**, 161 (1993).
  - [3] A. Airapetian, *et al.*, (HERMES Collaboration), Phys. Rev. Lett. **84**, 4047 (2000); Phys. Rev. **D 64**, 097101 (2001); Phys. Lett. **B 562**, 182 (2003); Phys. Rev. Lett. **94**, 012002 (2005).
  - [4] V.Y. Alexakhin, *et al.*, [COMPASS Collaboration], Phys. Rev. Lett. **94**, 202002 (2005); E.S. Ageev, *et al.*, [COMPASS Collaboration], Nucl. Phys. **B 765**, 31 (2007); Anna Martin (On behalf of the COMPASS Collaboration), Czech. J. Phys. **56**: F33 (2006), hep-ex/0702002.
  - [5] M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin, and C. Turk, Phys. Rev. **D 75**, 054032 (2007).
  - [6] X. Jiang, J.-P. Chen, E. Cisbani, H. Gao, J.-C. Peng, *et al.*, JLab E06-010 and E06-011.
  - [7] J. C. Collins and G. A. Ladinsky, hep-ph/9411444; J. C. Collins, S. F. Heppelmann, and G. A. Ladinsky, Nucl. Phys. **B 420**, 565 (1994).
  - [8] R. L. Jaffe, X.-M. Jin, and J. Tang, Phys. Rev. Lett. **80**, 1166 (1998).
  - [9] P. B. van der Nat (HERMES Collaboration), hep-ex/0512019.
  - [10] C. Schill (on behalf of the COMPASS Collaboration), arXiv: 0706.1459 [hep-ex]; C. Schill (on behalf of the COMPASS Collaboration), arXiv: 0709.4625 [hep-ex].
  - [11] M. Radici, R. Jakob, and A. Bianconi, Phys. Rev. **D65**, 074031 (2002).
  - [12] A. Bacchetta and M. Radici, Phys. Rev. **D 74**, 114007 (2006).
  - [13] A. Bacchetta, U. D'Alesio, M. Diehl, and C. A. Miller, Phys. Rev. **D 70**, 117504 (2004)
  - [14] A. Bacchetta and M. Radici, Phys. Rev. **D 69**, 074026 (2004).
  - [15] R. P. Feynman, *Photon Hadron Interactions* (Benjamin, New York, 1972), P 150.
  - [16] F. E. Close, Phys. Lett. **B 43**, 422 (1973); Nucl. Phys. **B 80**, 269 (1974); R. Carlitz, Phys. Lett. **B 58**, 345 (1975); J. Kaur, Nucl. Phys. **B 128**, 219 (1977); A. Schäfer. Phys. Lett. **B 208**, 175 (1988); F. E. Close and A. W. Thomas, Phys. Lett. **B 212**, 227 (1998); N. Isgur, Phys. Rev. **D 59**, 034013 (1999).
  - [17] B.-Q. Ma, Phys. Lett. **B 375**, 320 (1996).
  - [18] G. R. Farrar and D. R. Jackson, Phys. Rev. Lett. **35**, 1416 (1975).
  - [19] R. Blackenbecker and S. J. Brodsky, Phys. Rev. **D 10**, 2973 (1974); J. F. Gunion, Phys. Rev.

- D 10**, 242 (1974); S. J. Brodsky and G. P. Lepage, Presented at Summer Inst. on Particle Physics, SLAC (1979).
- [20] S. J. Brodsky, M. Burkardt, and I. Schmit, Nucl. Phys. **B 441**, 197(1995).
  - [21] M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. **D 63**, 094005 (2001).
  - [22] M. Hirai, S. Kumano, and N. Saito, (Asymmetry Analysis Collaboration), Phys. Rev. **D 69**, 054021 (2004).
  - [23] X. Chen, Y. Mao, and B.-Q. Ma, Nucl. Phys. **A 759**, 188 (2005).
  - [24] Y. Huang, J. She, and B.-Q. Ma, Phys. Rev. **D 76**, 034004 (2007).
  - [25] B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, Phys. Rev. **D62**, 114009 (2000).
  - [26] B.-Q. Ma, I. Schmidt, and J. Soffer, Phys. Lett. **B 441**, 461 (1998).
  - [27] B.-Q. Ma and I. Schmidt, J. Phys. **G 24**, L71 (1998); Phys. Rev. **D 58**, 096008 (1998).
  - [28] I. Schmidt and J. Soffer, Phys. Lett. **B 407**, 331 (1997).
  - [29] B.-Q. Ma, J. Phys. G: Nucl. Part. Phys. **17**, L53 (1991); B.-Q. Ma and Q.-R. Zhang, Z. Phys. **C 58**, 479 (1993).
  - [30] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. **D 63**, 037501 (2001).
  - [31] B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, Phys. Rev. **D 64**, 014017 (2001).
  - [32] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky, and W. K. Tung, JHEP **0207**: 012 (2002).
  - [33] B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, Phys. Rev. **D 62**, 114009 (2000).
  - [34] A. Bacchetta and M. Radici, Phys. Rev. **D 67**, 094002 (2003).
  - [35] B.-Q. Ma, I. Schmidt, and J.-J. Yang, Phys. Rev. **D 65**, 034010, (2002).